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Design and Integration Challenges for a Fuel Cell Hybrid Electric Sport Utility Vehicle

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ABSTRACT

Large sport utility vehicles have relatively low fuel economy, and thus a large potential for improvement. One way to improve the vehicle efficiency is by converting the drivetrain to hydrogen fuel cell power. Virginia Tech has designed a fuel cell hybrid electric vehicle based on converting a Chevrolet Suburban into an environmentally friendly truck. The truck has two AC induction drive motors, regenerative braking to capture kinetic energy, a compressed hydrogen fuel storage system, and a lead acid battery pack for storing energy. The fuel cell hybrid electric vehicle emits only water from the vehicle. The fuel cell stacks have been sized to make the 24 mpg (gasoline equivalent) vehicle charge sustaining, while maintaining the performance of the stock vehicle. The design and integration challenges of implementing these systems in the vehicle are described.

INTRODUCTION

In recent years, many initiatives have been enacted to clean the air, one of which was the proposed Kyoto treaty in Kyoto, Japan, in December 1997. This treaty was negotiated by more than 160 nations, and was designed to reduce certain greenhouse gases, mainly carbon dioxide (EIA, 1998). The agreement requires the reduction of greenhouse gas (GHG) emissions to 7% below the 1990 level (NCBA, 1999). The timeframe for this reduction to occur is 2008-2012 (TECO,1998). The main focus of this reduction will be in the energy use sector because this is the main source of greenhouse gas emissions (Hakes,1999). Under current energy production methods, that would mean a 41% reduction in energy consumption (TECO, 1998). The transportation sector contributes one-third of US GHG emissions, and is increasing faster than the industrial and building sectors.

Jay Hakes, administrator of the Department of Energy's Energy Information Administration (EIA), presented to the Energy and Natural Resource Committee of the United States Senate several ways to reduce GHG emissions and maintain the same level of energy consumption. His recommendations include a shift to nuclear and renewable sources of energy rather than fossil fuels, using fuels with less carbon intensity and use more energy-efficient technologies. With these ideas in mind, the Hybrid Electric Vehicle Team (HEVT) of Virginia Tech set out to convert an existing 2000 model Chevrolet Suburban to compete in the 2001 FutureTruck Challenge.

In an effort to address some of Mr. Hakes' suggestions as well as issues raised by the Kyoto treaty, the HEVT of Virginia Tech decided to employ a series hybrid design in their truck, named ZE*burban* (Zero Emission Suburban). This design uses a proton exchange membrane (PEM) fuel cell as its auxiliary power unit. The PEM fuel cell directly converts pure hydrogen fuel to electricity and water, which completely eliminates carbon and the possibility of forming carbon dioxide onboard the vehicle. However, the production, transportation and distribution of hydrogen generates carbon dioxide (and other greenhouse gasses) because the production process uses methane (CH_4), which is a low carbon-intensity fossil fuel (Wang and Huang, 2000). In the future, hydrogen can be produced from renewable sources, possibly eliminating greenhouse gas emissions from hydrogen production. Fuel cells have also demonstrated higher efficiencies than internal combustion engines. As part of the Kyoto treaty, the use of diesel fuel is to be reduced and eventually eliminated. Consequently, PEM fuel cell technology was chosen as an auxiliary power unit rather than a small diesel engine.

There are several advantages to using hydrogen as a fuel onboard the vehicle. Hydrogen has three times the energy content per mass as either gasoline or diesel

fuel. The down side to compressed hydrogen gas is low energy content per unit volume, making it difficult to store enough fuel onboard to match the range of a gasoline or diesel vehicle.

Industrial hydrogen fuel production is relatively clean as far as emissions are concerned. Hydrogen can be produced through electrolysis, or through the use of a steam reformer. Reformers use natural gas, or methane, along with steam to produce hydrogen and carbon monoxide. The carbon monoxide is then reacted with steam (water-gas shift reaction) to produce carbon dioxide and hydrogen. For every molecule of methane used in the process, four molecules of hydrogen are produced, and only one molecule of carbon dioxide is released. This process results in a significant reduction in GHG emissions when compared with combustion of gasoline or diesel fuel. Hydrogen has 71% less GHG emissions per unit energy over the whole fuel cycle relative to gasoline (Wang, 1999).

DESIGN OBJECTIVES

The 2001 FutureTruck Challenge specifies the following performance and emissions criteria for the converted vehicle:

- A goal of two-thirds reduction of total cycle GHG emissions as compared with emissions of the stock vehicle and gasoline fuel
- Achievement of California ULEV II exhaust emissions with comparably low evaporative and running loss emissions
- Maintaining of a fully-functioning vehicle with all working accessories and options of the stock vehicle
- Towing a trailer of up to 3175 kg (7000 lb) capacity.
- 0-60 mph acceleration time of less than 12 seconds
- Seating for 8 adults
- 0.65 cubic meters (650 L, 23 ft^3) of cargo capacity

The goal of our design is to ensure that the overall vehicle meets the FutureTruck criteria. Component sizing and selection is a major concern to meet the goals of FutureTruck for two reasons. The first reason is that the components must be sized appropriately. For example a traction motor must be able to supply enough mechanical power to accelerate the vehicle from 0-60 in less that 12 seconds. The second reason is that appropriately sized components must all fit into the vehicle without compromising the current vehicle capabilities and capacities.

Further design considerations are the balance required among selecting the most efficient drivetrain, implementing the fuel cell system, selecting the batteries, providing power to vehicle components, achieving vehicle performance and safety, as well as achieving consumer acceptability and ease of mass production.

A hybrid PEM fuel cell vehicle requires three main systems: electric drivetrain, the fuel cell, and energy storage (batteries). A more in-depth analysis of component selection considers the interactions and trade-offs between the main systems and vehicle energy efficiency, performance, safety, and mass production feasibility.

VEHICLE MODELING

Vehicle modeling is used to predict the size and trade-off between the drivetrain, battery storage, and fuel cell power output. Modeling is the key to properly sizing components and maintaining vehicle performance acceptable to consumers. The series hybrid electric vehicle (HEV) model was developed using ADVISOR, an advanced vehicle simulator of the National Renewable Energy Lab (Wipke, et al.,1999). Initially, a stock Suburban was modeled and validated in ADVISOR, using available test data. The model yields the power requirements necessary to move the stock vehicle. Replacing the stock internal combustion engine with a PEM fuel cell system changed the vehicle model and mass. Keeping in mind the performance requirements of FutureTruck, the PEM fuel cell system was reflected in the model.

Figure 1 shows the energy flow and component configuration for the fuel cell hybrid electric vehicle model. This vehicle model uses a electric drivetrain model validated at Virginia Tech (Merkle, et. al., 1997; Senger, et al., 1998). The fuel cell system model was scaled from a validated component model (Luttrell, et al., 1999; Fuchs et al., 2000; Ogburn, et al., 2000). The model has also been validated using test data from the 2000 FutureTruck Challenge results for ZE*burban* operating as a battery electric vehicle (Patton et al., 2001).

DRIVETRAIN SIZING

The drivetrain is sized to complete both of the EPA drive cycles, complete the towing events, and have comparable acceleration capabilities to that of the stock vehicle. Drivetrain sizing began by determining the power and energy requirements of the proposed hybrid vehicle from the stock vehicle model. The three driving cycles considered are the Federal Urban Driving Schedule (FUDS), the Highway Fuel Economy Test (HWFET), and a constant speed cycle at 105 km / hr (65 mph). These cycles are used to determine average and peak vehicle power requirements. The average vehicle energy requirements are used to select an appropriate drivetrain with average operation in a high efficiency region. For the competition, the vehicle should be capable of executing the EPA dynamometer drive cycles with a single axle. Table 1 contains the average cycle power and peak cycle power at the wheels of the vehicle for a 6800 lb. (3090 kg) vehicle weight.

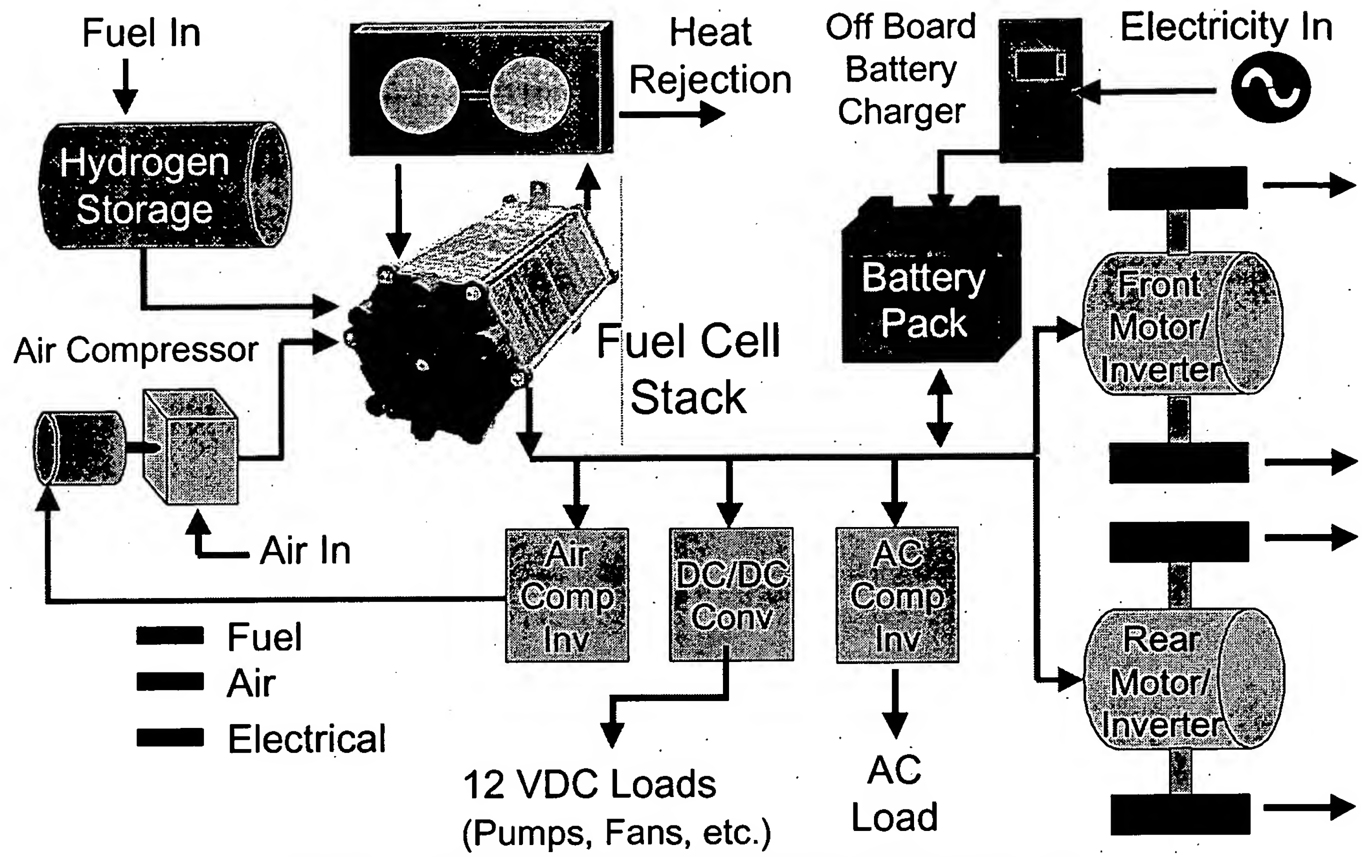

Figure 1. Energy Flow in the Fuel Cell Hybrid Electric FutureTruck

Table 1. Vehicle Road Load Power Requirements

	Average (kW)	Peak (kW)
FUDS	12.7	85.5
HWFET	20.3	68.5
Constant 65 mph	28.8	28.8

Design power requirements for the drivetrain have been determined from simulating a trailer being towed at 88 km/hr (55 mph) up a 5% grade. The combined vehicle and trailer weight was 5900 kg (13000 lbs.). The road load power required to maintain this towing on grade condition is 112 kW. The maximum power requirement of 150 kW results from the vehicle acceleration requirement of 0-60 mph in 12 s.

BATTERY SELECTION

Before we begin sizing and modeling batteries, we must specify the battery technology. There are several different types of batteries being considered for use in electric and hybrid vehicle applications. These batteries include lead acid, nickel metal hydride, lithium polymer, sodium nickel chloride, and nickel cadmium. Each of the categories in Table 2 represents specific characteristics to compare battery technology. The largest number in each category represents the best performance for that characteristic. The team first eliminated batteries that would not meet weight or size requirements.

Table 2. Rechargeable Battery Options

Technology	Wh/kg	Wh/l	W/kg	W/l
Advanced Lead-Acid	35	71	412	955
Nickel Metal Hydride	80	200	220	600
Lithium Polymer	155	220	315	445
Sodium Nickel Chloride	90	150	100	200
Nickel Cadmium	50	150	-	-

Nickel cadmium batteries were eliminated as a choice because cadmium is a hazardous material. Sodium nickel chloride batteries are too big and heavy to be considered for our vehicle platform. Lithium polymer has the best capacity comparison value, but have also been eliminated because of the lack of availability for use in HEV applications.

For use in ZE*burban*, power density (W/kg) is very important because a series HEV, like ours, needs to be able to source high power on a regular basis. Nickel metal hydride batteries have a good energy density (Wh/kg) and power density. However, nickel metal hydride batteries are very expensive and have been eliminated as a candidate. Advanced lead acid batteries have the highest power density (W/kg) of any batteries considered. These batteries are readily available, inexpensive relative to other batteries, and are used in many electric vehicle applications. Lead acid batteries also have relatively high charge/discharge efficiency for

low losses in a hybrid application. After considering these options, advanced lead acid batteries were selected for use in ZE*burban*.

CAPACITY SIZING FOR BATTERY STORAGE

There are two attributes for battery sizing, energy capacity and power. These attributes are dependant upon packaging, weight, degree of hybridization and vehicle energy use. Vehicle energy use is dependant upon the vehicle characteristics, such as weight, rolling resistance, aerodynamic drag and the vehicle drive cycle. To maintain usability of the vehicle, regardless of the operational status of the fuel cell systems, the vehicle must be able to run the FUDS and HWFET drive cycles using power only from battery storage. According to the vehicle and battery models, 26 Ah Hawker Genesis batteries will provide the nominal 4 kWhr necessary to complete each driving cycle. Battery capacity sizing also depends upon the size of the fuel cell systems or the degree of hybridization (Atwood, et al., 2001). Atwood shows that the interaction between the battery capacity and fuel cell system effects fuel economy. Using these results, the 26 Ah Hawker Genesis batteries are well suited for our fuel cell vehicle application.

FUEL CELL SIZING

The Department of Energy has made available an 80 kW Honeywell PEM fuel cell stack (Fig. 2) for the FutureTruck competition. However, the 80 kW gross peak rating depends on inlet reactant supply pressures of 3 atm. The overall system efficiency and net power available at the 3 atm operating condition are lower than desirable, and can be increased by reducing the system pressure. Operating at a lower system pressure significantly reduces the amount of parasitic air compressor power needed to run the fuel cell systems, but also reduces the maximum gross power available from the fuel cell stacks. We have decided to run our

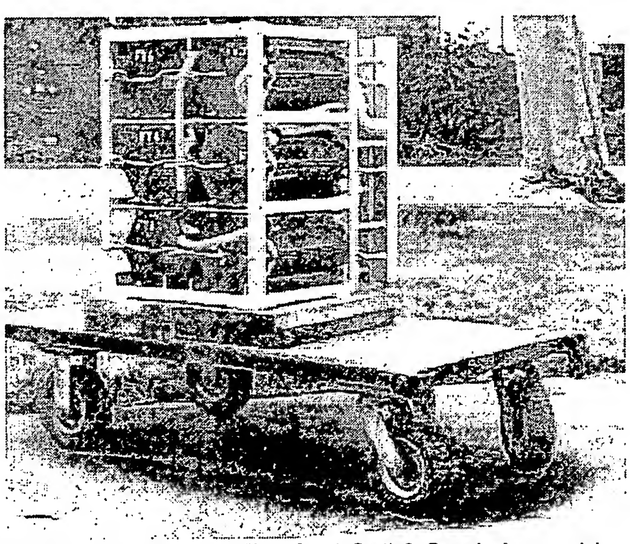

Figure 2. Honeywell PEM Fuel Cell 6-Stack Assembly

systems at 2 atm, which gives us 60 kW maximum gross power available from the stacks, or 49 kW of net power.

The fuel cell in a hybrid vehicle can be been sized to provide the average vehicle energy requirements. For cycles such as the FUDS, HWFET, or at a constant speed of 65 mph, 40 to 50 kW of net power would be ample. However this size gives a short range or reduced speed for higher power cycles such as towing or long grades. A fuel cell stack size of 100 kW gross output is needed to provide a net system power of greater than 80 kW for good towing and grade performance.

VEHICLE COMPONENT SIZING SUMMARY

Our fuel cell hybrid electric vehicle will use 60 kW gross of fuel cell stack power, a 4 kWh, 336 V nominal lead acid battery pack and 170 kW of electric drive power.

MODELING RESULTS

VEHICLE PERFORMANCE

Models of the stock vehicle 2500 kg (5400 lbs.) and the converted fuel cell hybrid vehicle 3090 kg (6800 lbs.) were run in several full power tests. These tests include accelerations both with and without a 3175 kg (7000 lbs.) trailer. The results are shown in Table 4. Based on the models used, the converted vehicle meets the performance of the stock vehicle in the areas that are considered. The converted vehicle is geared for a top speed of 130 kph (80 mph).

Table 4. Performance estimation results

	Stock	Converted
0 to 30 mph (sec)	3.9	2.9
0 to 60 mph (sec)	9.9	10.3
1/4 mile time (sec)	17.6	17.7
with 7000 lb trailer		
0 to 30 mph (sec)	8.1	6.3
0 to 60 mph (sec)	22.4	21.7
1/4 mile time (sec)	24	22.3

ENERGY EFFICIENCY AND FUEL ECONOMY

Using the modeling results from ADVISOR software, we were able to determine the vehicle energy efficiency and fuel economy. Using component sizes from above, we evaluated ZE*burban* on two different driving cycles: Fedral Urban Driving Cycle (FUDS), and Highway Fuel Economy Test (HWFET). The FUDS test includes an approximation for fuel cell cold start efficiency. Overall fuel economy (unadjusted) results are compared for four cases in Table 5. The values given for the fuel cell

vehicle are for no net change in battery state of charge and a weight of 3090 kg (6800 lb). The first two columns present available measured data for the stock vehicle. The third column shows good agreement between an ADVISOR model of the stock vehicle and this data. The ADVISOR model for the ZE*burban* design shows a combined city/highway fuel economy of 24.2 mpgge, or a factor of 1.4 increase over the stock vehicle. This increase is due to the combination of an efficient electric drivetrain, regenerative braking, and an efficient fuel cell system running at relatively light average load.

Tabl 5. Fuel Economy Comparison

Driving Cycl (mpgge)	Stock Vehicle (GMTG)	Stock Vehicle (EPA)	Stock Vehicle (ADVISOR)	Fuel Cell Vehicle (ADVISOR)
City	13.5	14.9	15.2	23.3
Highway	20.0	20.6	20.3	25.2

GREENHOUSE GAS IMPACT AND EMISSIONS

Greenhouse gas emissions (GHGE) directly relate to fuel economy; an increase in fuel economy decreases greenhouse emissions. A zero emissions vehicle, such as ours, is truly not a zero emissions vehicle because of upstream GHGE from hydrogen fuel production. Fuel production and upstream GHG generated emissions are considered in our vehicle's GHG impact on the environment. Hydrogen is efficiently generated using natural gas. Natural gas is a low carbon intensity fuel that contributes less carbon dioxide during processing than other hydrocarbon fuels.

The greenhouse gas impact for our vehicle is based upon all emissions from hydrogen production and distribution from well to tank for fuel used by the vehicle. Fuel use is determined from our modeled vehicle fuel economy. The predicted fuel economy on the FUDS driving cycle is 23 miles per gallon gas equivalent (mpgge) and 25 mpgge during the HWFET cycle. Using the GREET model (Wang, et al., 1999) for hydrogen production, our vehicle design yields a reduction of 85 % in greenhouse gas emissions, exceeding the FutureTruck goal of 67% reduction. Table 6 shows the weighted comparison of greenhouse gas emissions for the FUDS and HWFET driving cycles.

Table 6. Comparison of weighted greenhouse gas emissions on EPA drive cycles

GHG Index	City	Highway
Stock Suburban	1043.7	1063.6
ZE*burban*	148.6	117.1

These cycles are not usually representative of consumers actual driving habits, which increase the in-use GHG impact and fuel use of vehicles. These increased vehicle emissions are called off-cycle emissions. The efficiency of our fuel cell systems have only a 10% efficiency penalty when operating at high power conditions. Vehicle emissions do not increase during off-cycle conditions with a fuel cell system, only fuel consumption increases. Therefore our vehicle design, even during off-cycle conditions, will impact GHG emissions less than conventional vehicle technology. The ZE*burban* fuel cell vehicle is also locally zero emission with no evaporative emissions.

A summary of the overall specifications for the vehicle design and component selection are given below. The following sections give detailed descriptions of each of the major systems on the vehicle.

HYBRID VEHICLE CONSTRUCTION

ELECTRIC DRIVETRAIN

The desired characteristics for the electric drivetrain system are high efficiency, compact packaging, low weight, high maximum speed, and high power. The ZE*burban* is a series fuel cell hybrid, so the electric drivetrain is responsible for all of the motive force of the vehicle. To maintain four-wheel-drive operation and near stock performance using available size components, two separate drivetrains are used.

A dual GE system was chosen for its packaging, continuous power output, higher maximum speed, and higher efficiency. The front axle is driven by a GE MEV-75 motor mounted in the original front differential location and a GE EV2000 motor was placed in the rear of the truck behind the rear torsion bar support. The GE EV2000 uses a custom, slip-joint, driveshaft and propels the rear axle through a non-locking GM differential with a 3.73:1 reduction. This packaging configuration has the advantage of allowing the area occupied by the original transmission and transfer case to be used for other systems.

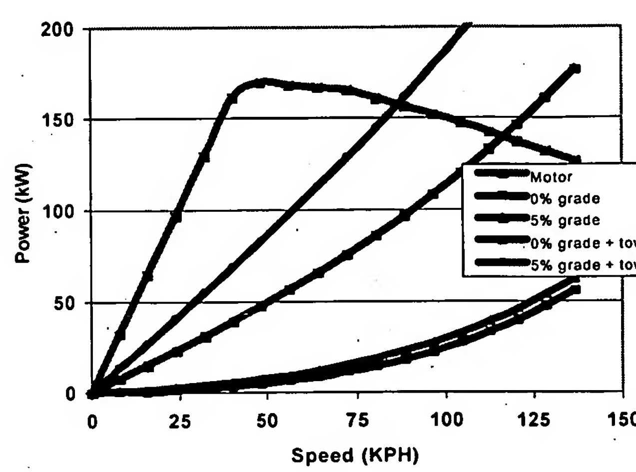

Figure 3. Drivetrain Performance for Vehicle Loads

These motors have a continuous power rating of 60 kW (80 hp) at 3000 rpm and a peak power rating of 85 kW (114 hp) at 4000 rpm. The maximum rotor speed is electronically governed to 13,500 rpm. The torque at the rotor is constant at 195 N-m (143 ft-lb) from 0 to 4000 rpm, and then decreases with speed to 40 N-m (30 ft-lb) at 13,500 rpm as the motor operates in near constant power mode. The MEV-75 boasts a planetary gear set with a gear ratio of 12.18:1, and differentials are housed inside the lightweight aluminum-magnesium alloy transaxle motor case. The EV2000 motor uses a heavier aluminum case and has a planetary gear reduction of 4.29:1 to a simple U-joint coupling. Since the final drive of the rear drivetrain is a steeper 16:1 compared with the front's 12.18:1, the limiting speed had to be determined. With the 265-75-R16 tires that the HEVT is using, the top speed of the rear motor at 13,000 RPM is 80 mph. The speed limit of the front motor is also set to a similar top road speed. This arrangement is to insure that the front motor does not try to pull the vehicle while the rear reaches its maximum rotational speed. The combination of these features provides the Virginia Tech team with an ample-powered drivetrain system (see Figure 3) in a convenient package for our vehicle.

INVERTER

Both motors utilize a General Electric EV2000 inverter. These two inverters control each AC induction motor, which is designed for maximum part load efficiency by using a two-mode, six-step technique to control current in each of the motor windings. At lower speeds and torques, the switching is pulse-width modulated over a range of frequencies, while at higher speeds and torques, the devices are hard-switched in a typical six-step scheme. Switching is performed by three Toshiba IGBT module pairs, which are rated at 400 A and 600 V. The motor control feedback loop consists of a two channel optical hall-effect tachometer sensor for basic variable slip control of the drive, as well as quadrature flux sensors, which maximize drive performance by allowing the inverter to operate the motor near magnetic saturation.

The basic design provides 145 ft-lb of stall torque when supplied from a 300-amp inverter. The motor/inverter efficiency is more than 90% from maximum torque down to torque values of 5 ft-lb (3.5% of maximum). The inverter controller adjusts the motor flux level and basic modulation frequency to reduce both the motor and inverter losses when operating at low torque. A midsize 1450 kg (3200 lb) test weight Ecostar vehicle on the Federal Urban Driving Schedule operates with an overall energy consumption, (including accessory load) of 235 watt-hours/mile (147 watt-hrs/ton-mile). The efficiency and performance are well matched to the requirements of a light-duty electric drivetrain at the operating areas of interest, which include part-load and half speed.

The EV2000 inverter features several safeguards to ensure maximum performance under limiting conditions. A temperature sensor embedded in the stator windings allows the inverter to reduce drive power to protect the motor under high operating temperatures. Temperature sensors within each IGBT pair allow the inverter to provide maximum performance while simultaneously guarding against device failure from overheating. Traction battery voltage is also carefully monitored under load. The inverter begins current limiting as soon as the traction battery drops to 60% of its nominal voltage. This design gives the inverter a "limp-home" mode that allows the vehicle to be driven at low power with nearly depleted batteries until they can be recharged.

The EV2000 inverter is designed to emulate a conventional automobile through such features as a creep mode, which simulates the creeping action of an automatic transmission, and regenerative braking to replace friction braking. An easy-to-use software interface allows the user to customize several control options.

PACKAGING DESIGN

The packaging design of the FutureTruck has an impact on the durability, serviceability and feasibility of the overall success of the vehicle. Packaging of the vehicle also has an effect on the safety and crashworthiness related issues considered with the vehicle.

OVERALL PACKAGING DESIGN

Packaging of the larger and heavier components is given the highest importance. Another guideline is to reserve space in the engine bay for components related to the fuel cell systems. Components with rotating parts (pumps, motors and fans) are mounted to the frame rather than the body to reduce noise and vibration. The overall packaging design is shown in Figure 4.

The rear power module is located in the center of the vehicle, between the rear axle and transmission mount. This places the large mass of the batteries low to the ground for decreased center of gravity and ease of serviceability. The location of the batteries also allows simple removal with a vehicle lift. Another reason that this location is chosen is for its close proximity to all of the other high voltage components such as traction motors and their subsystems.

The design of the our truck requires two traction motors. The motors can connect mechanically to the vehicle either in a single ended U joint coupling, or a transaxle halfshaft configuration. Two design configurations were considered using two single ended motors or a single ended motor with a transaxle motor. The first configuration used two single ended motors with the U joint coupling. One of the motors would connect to the

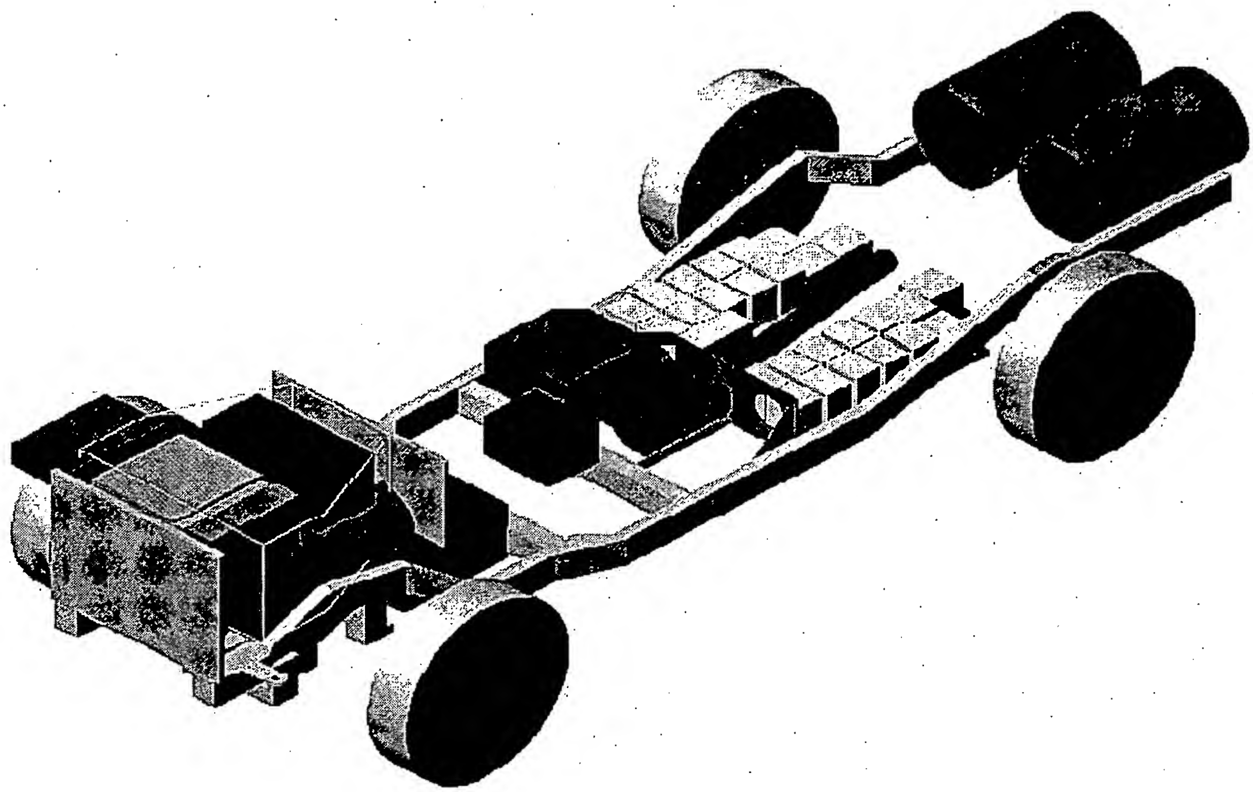

Figure 4. Component Packaging Diagram

existing rear drive shaft, while the other would connect to the front drive shaft from the transfer case. Because of the motor size and a lack of ground clearance for the front motor, this design was considered unusable. So the motor that would have plugged into the front axle was replaced with a transaxle motor. The rear motor was then integrated into the battery box.

The motor controllers or inverters need to be close to the motors that they drive to reduce radiated electrical noise. To reduce heavy wiring for the system, the inverters need to be located close to the batteries and the contactor box. With the previously mentioned restraints and useable space under the vehicle, one inverter was located under the vehicle between the transaxle and contactor box. The other inverter was integrated into the rear power module, next to the rear drive motor. This layout allows the remaining fuel cell systems to be located in the engine bay of the vehicle, and the hydrogen storage tanks are located where the spare tire would normally exist. The spare tire is relocated to the interior of the vehicle.

FUEL CELL SYSTEMS

Virginia Tech has chosen to use a proton exchange membrane (PEM) fuel cell system. A PEM fuel cell requires oxygen from air, hydrogen and cooling water delivered at the appropriate pressure, temperature, flow-rate and humidity. The components required to deliver these fluids plus the fuel cells are what make up the fuel cell system, as shown in Fig. 5.

HYDROGEN STORAGE AND DELIVERY OPTIONS

Several hydrogen storage methods were considered to provide our vehicle with adequate storage to maximize the mass of hydrogen that can be stored on board the vehicle. The four types of storage that were explored were metal hydrides, cryogenic liquid, reformed hydrocarbon technologies, and compressed gas. Metal hydrides were not used because the tanks have relatively low energy density, or the ability to store many kg of hydrogen per kg of tank weight. Metal hydrides also require cooling to fill, and heating to extract the hydrogen, which complicate vehicle integration. Liquid hydrogen was also not chosen because it must be stored at 20 K, which has its own safety concerns. Maintaining the hydrogen at this temperature would induce a large parasitic loss due to energy required for refrigeration. Additionally, unavoidable boil-off could cause standby losses of up to 5% per day. A review of hydrogen storage costs can be found in James et al. (1994).

Hydrocarbon reformers have the advantage of using existing fueling infrastructure, and significantly increase vehicle range. Hydrocarbon reformers were not used because of the lack of development of a practical vehicle reformer system. Current reformer technology is not

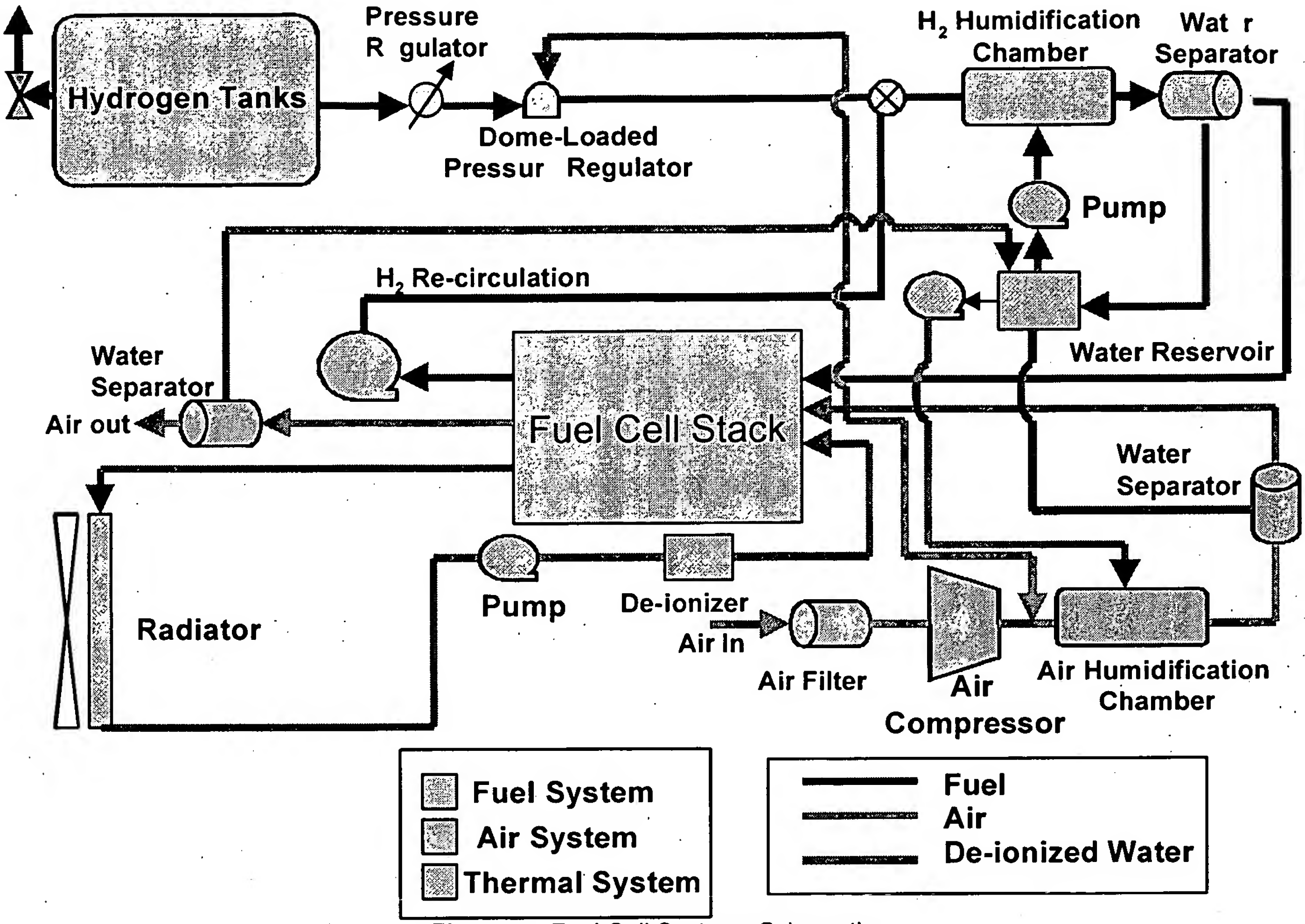

Figure 5. Fuel Cell Systems Schematic

small or lightweight enough for integration into our vehicle. We decided to use compressed gas tanks to store our hydrogen, mainly because this method has the highest energy density (kg hydrogen/ kg tank) currently available. In addition, there is no refrigeration or energy required to transport the hydrogen from the stored state to the fuel cell.

The tanks selected are provided to the FutureTruck Competition by Quantum Technologies through the U.S. Dept. of Energy. The tanks are rated at 35 MPa (5000 psi) and achieve a storage density of 7.5 % kg H2/kg. Due to safety considerations and limitations on available sizes, we were limited to two tanks, each of 61 l (16 gal) capacity, to fit under the rear of the vehicle between the frame rails. This tank size and mounting location limits the total mass of hydrogen that can be stored to 3 kg. Range with this limited storage is about 120 km (75 mi). The stock gasoline tank is approx. 130 l (34 gal) 105 kg (230 lb), which provides the stock vehicle with over 500 miles of range.

Our design for a hydrogen tank mounting system is illustrated in Figure 6.

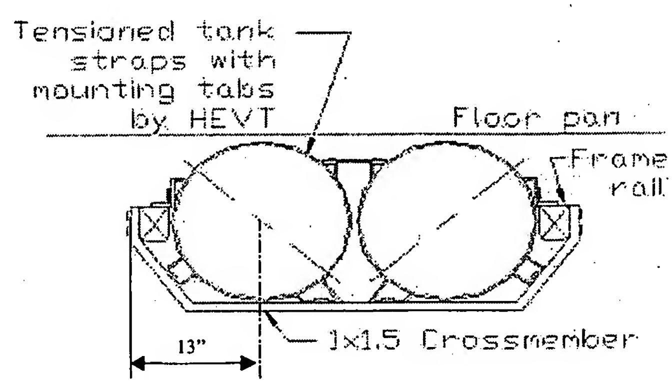

Figure 6. Hydrogen Tank Mounting

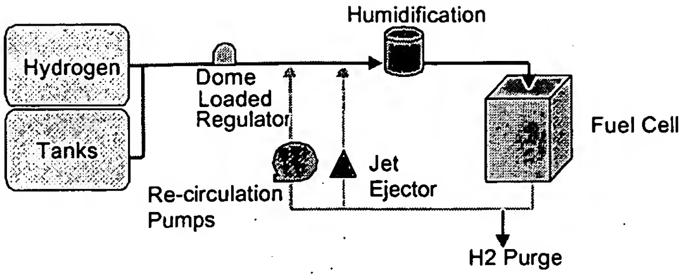

Figure 7. Fuel System Components

FUEL SYSTEM COMPONENTS

Power is extracted by the fuel cell from the electrochemical reaction of hydrogen and compressed air. Hydrogen must be delivered to the fuel cell at the correct temperature, pressure, mass flow and humidity. To achieve these requirements the team has implemented several systems: humidification, pressure regulation, re-circulation, and sensors that monitor and control hydrogen flow. The fuel system components are shown in Figure 7. The fuel system has been designed with safe hydrogen handling in mind (Kraft and Khier, 2001). Therefore, we have implemented safety systems into the design of the fuel storage and delivery system.

The inlet conditions of the fuel cell require that the pressure of the air and hydrogen be matched to prevent damage to the membrane. A dome-loaded regulator will regulate the pressure of the hydrogen in reference to a pressure of the air supply to the fuel cell. The inlet operating pressure range for the fuel cell will be maintained between 3 and 15 psi.

Another inlet condition requires that the hydrogen be humidified to at least 80% relative humidity. This will prevent the membrane from drying, which can damage it. The humidification system consists of fogging nozzles that spray atomized water into the flow of the hydrogen. Hydrogen re-circulation also contributes to humidification of the inlet hydrogen.

To increase the efficiency and range of the vehicle, hydrogen is re-circulated back into the inlet of the fuel cells. The purpose of the re-circulation is to reuse unconsumed hydrogen exiting the fuel cell stack, and re-circulate it back into the inlet of the fuel cells. There are two major components of the re-circulation system: four diaphragm pumps and one hydrogen jet ejector. The pumps and ejector are set up in parallel and are placed between the exit of the fuel cell stack and the inlet of the humidifier. The ejector re-circulates hydrogen for high loads. For the flow rate of hydrogen at high loads, a motive pressure of about 45 psig is needed for the ejector to supply hydrogen at the proper conditions to the fuel cell. At medium loads, the ejector needs a motive pressure of about 30 psig. Since the ejector will not work properly if the motive flow rate of hydrogen is too small, it will not provide sufficient re-circulation under low loads. The diaphragm pumps will begin to re-circulate during these instances.

Due to our re-circulation system, any non-reactive impurities in the hydrogen will build up in the fuel cell and hydrogen system, creating the need for a purging system. A solenoid valve is used to occasionally purge exhaust gasses through a flash arrestor. This purge valve will also vent hydrogen pressure when the system is not generating power. The purge valve is a normally open type, which opens the fuel cell stacks to the atmosphere. Opening the stacks to the atmosphere will insure that any reactants consumed in the fuel cell will not draw a vacuum and damage the membranes.

AIR AND HUMIDIFICATION SYSTEM

The air supply system provides the fuel cell with pressurized air at 80 °C and 50 – 80 % relative humidity. The pressure and flow rate vary with the fuel cell load. An overview of the air supply system is shown in Fig. 8.

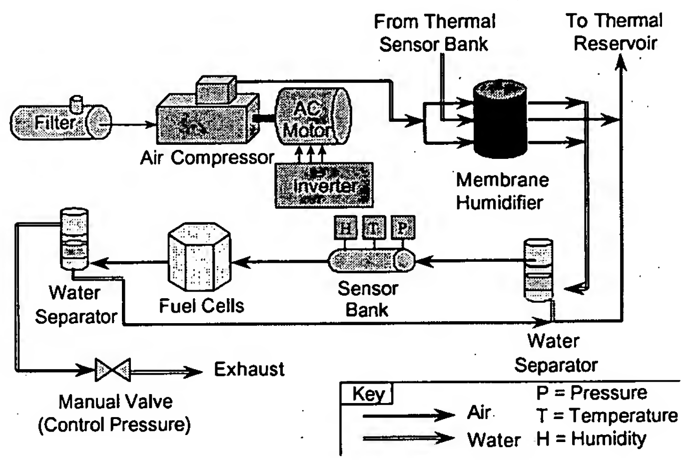

Figure 8. Air Supply and Humidification Components

The air intake filter is used to separate any particulate dust and road grime. The air is then be pressurized and supplied by an Opcon 1050A Twin Rotor compressor, driven by a low cost 10 kW, AC induction motor custom designed to be efficient for this application.

The output of the compressor is humidified by a custom Porvair membrane humidifier. Stainless steel membranes inside the Porvair unit act as a heat and mass transfer device. Heat energy from the thermal rejection system is used to drive the energy transfer required to humidify the inlet air stream. The humidifier has the capability of humidifying the air stream to 95+% relative humidity. Humidity is controlled between 50% and 80% using a solenoid valve that bypasses the humidity chamber. Water for the humidifier is taken from the thermal system by tapping into the coolant outlet of the fuel cells.

Temperature, pressure and humidity of the air is monitored at inlet of the fuel cell for control feedback to

the system. After the fuel cell stack, the air stream runs through a water separator to recover any condensed water and return it to the thermal reservoir. A fixed restriction is used to maintain a backpressure that varies with flow rate during nominal operation of the system.

THERMAL SYSTEM

The objective of the thermal system is to dissipate approximately 60 kW of heat generated by the fuel cell during operation. This task is completed using a flow of deionized water into the fuel cell at approximately 75 °C, which absorbs thermal energy and exits at 85 °C. A diagram of the thermal system components is sown in Figure 9.

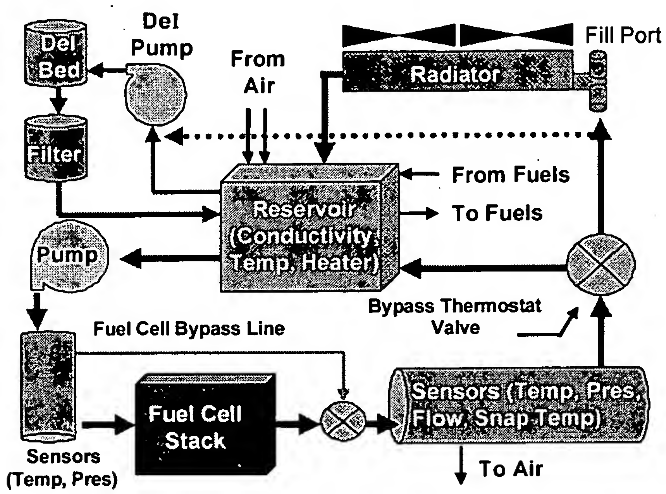

Figure 9. Thermal System Components

Our system is powered by a variable-speed centrifugal pump which has the capability of flowing up to 150 l/min (40 gpm) and overcoming 200 kPa (30 psi) of pressure loss. We have selected a low cost 0.75 kW (1hp) AC induction, industrial drive for this purpose based on the thermal properties of water and the 60 kW heat load. The heated coolant flows from the fuel cell stack through the stock aluminum radiator where fans supply a sufficient air flow to drop the temperature back to the desired inlet conditions for the fuel cell. Several secondary components are designed into the system to allow for variation in the temperature of the water.

Due to the temperature requirements of the fuel cell, a thermostat valve has been placed before the inlet to the radiator, so that when the water flow is too cold (under the expected 75 °C), the water bypasses the radiator so that it is not further cooled. This allows the system to continue heating itself through the fuel cell until it reaches the operating temperature, which increases the fuel cell efficiency.

The combination of the fuel, air and thermal systems, accounting for the parasitic power used by these systems, results in a net system power of 49 kW shown in Fig 10. The system efficiency is about 50% at the nominal operating point of 35 kW net, and improves at lower loads. The minimum fuel cell load the hybrid system will operate at is 10 kW and corresponds to the maximum efficiency. Due to minimum speed requirements for the air compressor and coolant pump, the system efficiency drops off at lower stack power.

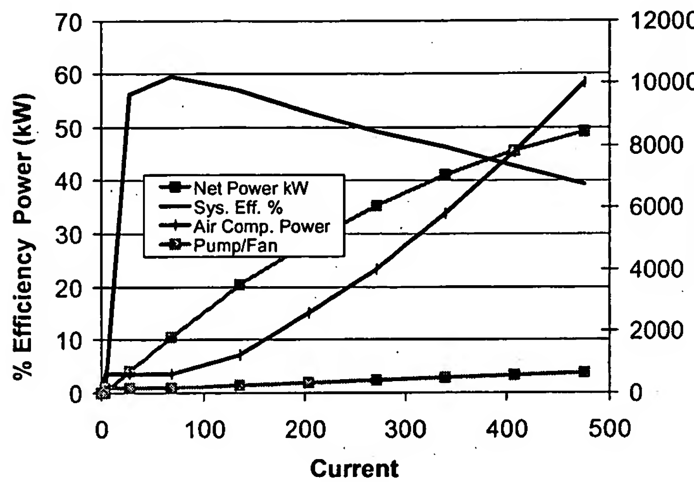

Figure 10. Fuel Cell System Part Load Characteristics

CONTROL SYSTEM

The control system is designed to start up, monitor and shutdown of the fuel cell and its subsystems. The control system drives a LCD touch screen user interface that provides communication between the driver and the control system. The control system reads all the sensors from the fuel cell subsystems and logs the acquired data. Logic in the control code determines what actions need to take place depending on the state of the individual systems.

At the heart of the control system shown in Figure 11 is a single board computer (SBC). The SBC runs the control code. Two data acquisition boards are stacked on the single board computer, enable the computer to sample signal from sensors, as well as send out control signals to the actuators in the system. All these elements are invisible to the user. A touch screen serves as interface between the driver and the vehicle. Vital information, messages and status of the system are transmitted to the user by the way of the GUI. An internal eithernet network in the ZE*burban* enable the SBC to feed to touch screen with the information the driver desires. This network makes it possible to plug additional laptops to the system, to download logged data or perform a check up of the SBC.

The operating system that the SBC uses is QNX, a real time operating system to handle data acquisition and provides a easy to use graphical environment.

For a fuel cell to perform efficiently, the air and the hydrogen fed to it need to be at very specific conditions

(i.e. temperature, pressure, humidity,...). To ensure the optimal operating conditions for the system, the control system monitors 34 different sensors. Data is logged for temperature, pressure, and humidity for the reactant and coolant flows. All the data allows performing a complete energy balance on the vehicle and enabling us to further identify the behavior of fuel cells in a mobile application.

This primary use for the data is to allow the control system to make decisions. The controls system operates the 17 actuators, including pump, solenoids and actuators in the vehicle. The control code specifies the interactions between sensors and actuators for example: if current on fuel cell increases, the air compressor speed increases.

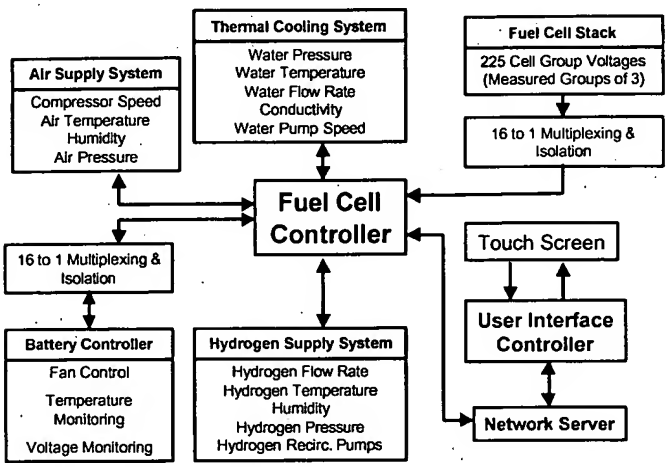

Figure 11. Control System Diagram

The six fuel cell stacks, from Honeywell, are composed of 105 cells per stack. Each cell produces a voltage between .5 V an 1.0 V. The voltage is a function of the fuel cell load and reactant conditions. The cell voltages are monitored to verify that the stack is operating properly. Cell voltages are monitored in groups of three cells, so there are a total of 210 voltages. If a group of three cells does not produce the expected voltage the control system shut down the fuel cell system. The 210 voltages are monitored through 15 multiplexing and isolation boards designed and implemented by the HEVT controls team.

Five major operating modes are identified and are controlled in the fuel cell system:

- Start-up
- Normal operating
- Shut down
- Emergency shut down
- Refill procedure

CONTROL STRATEGY

The electrical power from the fuel cell recharges the battery pack in the ZE*burban*. The control system starts the fuel cell system if the state of charge (SOC) of the battery pack is less then 40%. When the SOC of the battery pack reaches 80%, the fuel cell system is shut down and ZE*burban* powers the drivetrain off the battery pack. While the system is on, the fuel cell load varies with bus voltage and vehicle load to minimize the amount of power processed through the battery pack. This strategy has been tested through modeling and proves to be very efficient.

BATTERY IMPLEMENTATION

The design of the battery box structure and mounting, thermal considerations, and battery safety measures in case of a vehicle accident are presented below.

MECHANICAL DESIGN OF BATTERY BOX AND INTEGRATION INTO VEHICLE

The battery box is divided into two compartments and contains twenty-eight 12 volt batteries producing 336 V, an electric motor and an inverter. It also contains three fuses that protect the entire high-voltage system from current above 800 amps.

The battery box is installed under the vehicle in the location originally occupied by the fuel tank and exhaust pipe. The batteries sit on top of a chromoly steel box-beam frame lined with haysite material. Haysite is a strong fiberglass resin material with excellent electrically insulating properties. Steel brackets welded to the vehicle frame support the battery box. There are three brackets on each side of the battery box with three 5/16" bolts in each bracket. The end of the box is supported by uprights that attach to a steel brackets on the frame cross member. The batteries are kept in place by a tie down system that will consist of four nylon straps with ratchet buckles. Each strap is looped over each battery and through tie down points on the frame on the battery box. A lightweight polypropylene lid is placed over the platform to protect the batteries from the elements.

Two small fans are used to remove hydrogen that possibly could be released from the batteries during charging. Each fan has a capacity of 17 cfm. To cool the batteries during and after operation, larger impeller-type fans pull air through the plenum system. A diagram of the battery box cooling design is shown in Figure 12. An analysis was performed to determine how much air flow was needed, and where the fans would operate. Assuming the heat lost due to conduction and radiation to be negligible, the estimated required airflow was determined to be about 50 cfm for a steady 100 A load. The operating point between the system and the fans was determined to be about 95 cfm. This is enough flow to cool the batteries at a 100-amp steady load, plus momentary increases in current during a standard driving cycle.

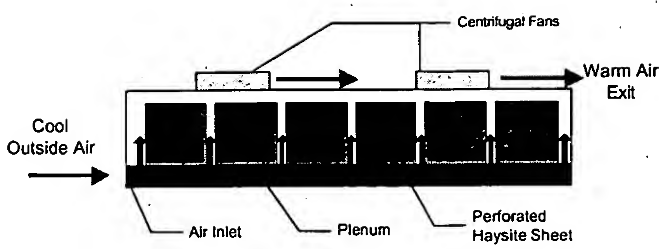

Figure 12. Battery box cooling design

The battery box consists of twenty-eight 26 Amp-hr batteries wired in series. The interconnects are made of 3/0 copper welding cable with soldered copper connectors. The welding cable is rated for 600 amps steady current. The cables are covered with insulation rated at 600 volts and 105°C. The battery and rear motor assembly, known as the rear power module is shown in Figure 13.

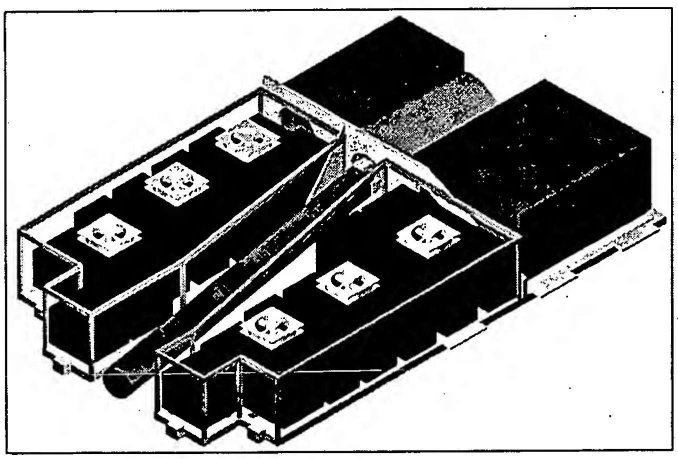

Figure 13. "Rear Power Module" Integrated battery and rear motor structure

ELECTRICAL SYSTEMS

The ZE*burban* series hybrid design requires several electrical systems. The systems are broken down into two sections: high voltage and low voltage. The high voltage system loads include the motors and their controllers, the DC/DC converter, the heating system, and the air conditioning system. The low voltage system loads include all the stock vehicle systems as well as some special 5, 12, and 15 volt control system loads. It is also important to monitor energy flow in and out of the battery pack. All of these issues are discussed in more detail below.

HIGH VOLTAGE

ZE*burban*'s high voltage electrical system varies from approximately 250 to 400 volts depending on load and state of charge of the vehicle's battery pack. The main distribution point of the high voltage is the vehicle contactor box. The box houses nine contactors that connect high voltage to the devices. The box also contains two pre-charge relays, one for each motor inverter, and a ground fault detection system. The high voltage system can be charged with either the on board fuel cell system or the vehicle's off board charging system. This charging system uses inductive charging technology to deliver power directly to the vehicle's battery pack. To allow maintenance, the high voltage system includes a lockable manual interrupt system (MIS). This system allows the high voltage bus to be severed at the battery pack and locked so that high voltage cannot flow to the rest of the vehicle. A schematic of the high voltage system is shown in Figure 14.

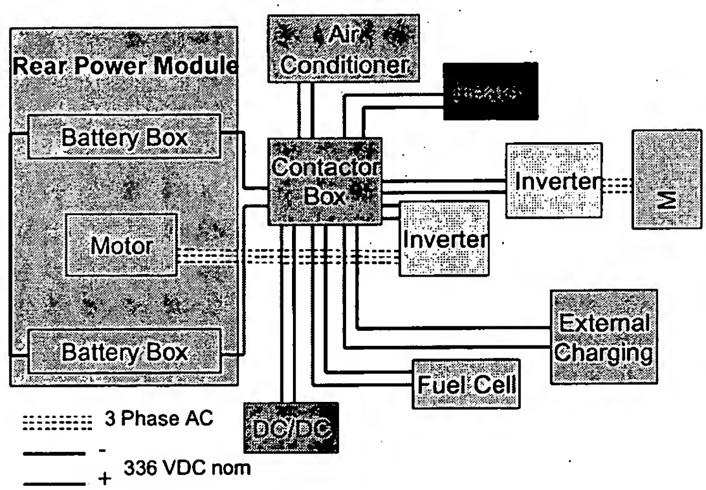

Figure 14. High Voltage Distribution and Control

The low voltage system in the truck consists solely of vehicle accessory loads. The stock accessory systems such as power locks, windows, and new electro-hydraulic steering are operated by a 3 kW DC-DC converter. This converter transforms the high voltage of the battery pack into 13.8 V DC, functionally replacing the stock vehicle's alternator. To start the vehicle, a standard 12 V battery is used to close high voltage contactors allowing the DC-DC converter to power up. A second smaller DC-DC converter supplies regulated 5, 12, and 15 V to various control circuitry throughout the vehicle.

POWER MONITORING

The power monitoring system consists of two E-meters and two current monitoring devices. The two E-meters monitor voltage and current flow of the battery pack and fuel cell system respectively to track power usage and overall battery pack amp-hour capacity. Two current monitoring devices are located in the vehicle contactor box and relay the current draw of each motor drive to that motor's respective controller.

FUEL CELL-HYBRID ELECTRIC VEHICLE SAFETY

Fuel cell hybrid electric vehicles have unique safety requirements because of the technology employed on the vehicle. Areas of concern include hydrogen storage, and high voltage. All of the stock safety features such as the air bag, and antilock braking system have been retained. Other safety features include the OnStar system, and the AutoPC, a voice activated radio.

HYDROGEN STORAGE SAFETY

A significant amount of design and development has been done to ensure that hydrogen does not escape the storage and delivery systems. However, hydrogen sensors are used to alert passengers in the event of a leak. The detectors can sense 1% volume of hydrogen in air, or 25% of the lower explosion limit. At 1%, the hydrogen detector will flash a yellow LED and sound an 80 dB alarm. When it detects 2% volume of hydrogen in air, the sensors will flash a red LED, and sound an 80 dB alarm. The alarm will trigger the opening of the rear and

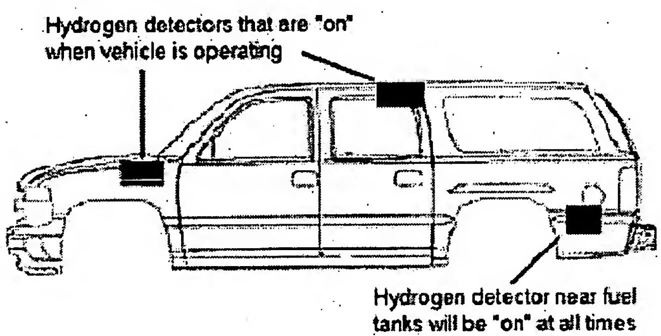

Figure 15. Hydrogen Detector Locations

side door windows. In addition, the sensors will terminate hydrogen flow at the tanks. Three hydrogen sensors are located in the engine bay, the dome of the passenger compartment, and above the fuel tanks. The locations of the hydrogen sensors are shown in Figure 15. The vehicle is equipped with service manual ball valves that prevent the flow of hydrogen from the tanks. The manual ball valves are located after the electric tank solenoids, in the rear of the vehicle.

HIGH VOLTAGE SYSTEM SAFETY

Incorporated on the vehicle are safety systems for high voltage electricity. There are two sources of high voltage electricity on the vehicle, fuel cells, and batteries. The battery pack of the vehicle uses high voltage and current contactors designed to interrupt the high voltage connection from the battery pack. These contactors are controlled four ways, as shown in Figure 16. The first is normal vehicle key operation. When the vehicle key is turned on, the contactors are enabled, and conversely if the key is turned off the contactors are turned off. An emergency smash switch is located on the rear bumper, which turns off the contactors when pushed. The third way is a removable, watercraft kill switch where a pin is removed to disable the contactors. The contactors cannot be enabled until the pin is replaced. The last way the contactors are disabled is an inertial kill switch. In the event of a collision, the inertial switch is activated which also disconnects the contactors.

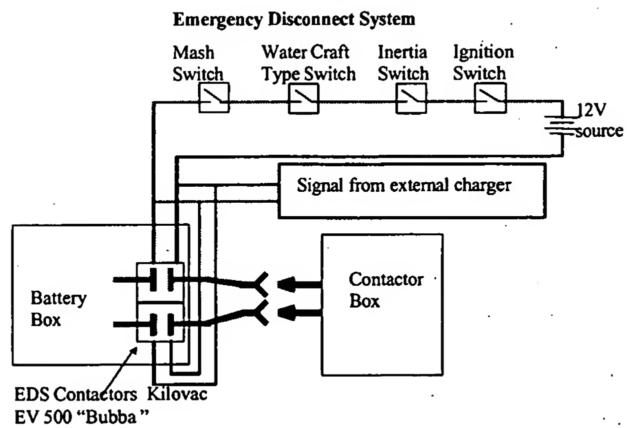

Figure 16. Emergency Disconnect System Diagram

INTEGRATION CHALLENGES

Fuel cell vehicles have barriers and challenges with specific technologies that need to be addressed in order to take these vehicles from the laboratory to a consumer's driveway. Consumer expectations of the vehicle capabilities drive many of the challenges or problems that need to be addressed and solved.

PACKAGING ISSUES

Packaging a conversion fuel cell hybrid vehicle is the most difficult task to successfully complete. The difficulty stems from the fact that a conventional technology vehicle has not been designed to accommodate fuel cell systems. A considerable amount of flexibility could be gained if a fuel cell vehicle is designed from the ground up to specifically

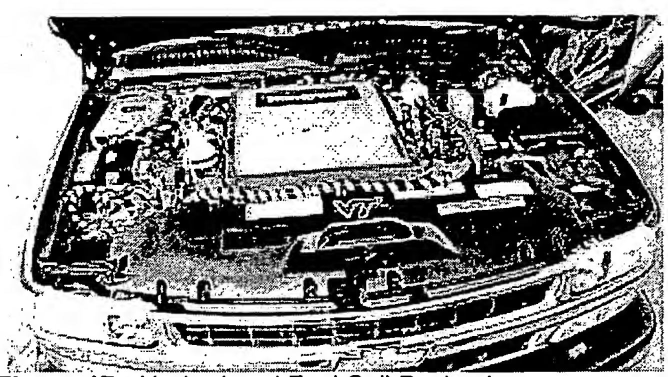

Figure 17. Under-hood Fuel Cell Packaging

accommodate fuel cell systems. Figure 17 shows the fuel cell systems packaged under the hood of the vehicle, with no room left to spare.

HYDROGEN STORAGE

Locating space for onboard hydrogen fuel storage is another challenge that is ongoing. Utilizing current technology compressed hydrogen storage still yielded 1/5 of the current conventional vehicle range. Additional range could be achieved by increasing the vehicle efficiency (weight reduction, aerodynamic improvements and overall fuel cell system efficiency) and increase the allocated space for hydrogen storage by reducing the size of other vehicle components.

FUEL CELL AIR SUPPLY SYSTEM

The air supply system, as previously described, uses a Opcon 1050A twin screw compressor, and a 10 kW, 10,000 rpm AC induction motor. A 10 kW industrial motor drive provides the control for the AC induction motor. The setup yielded a 60 kg system that measures approximately 0.75 m in length, and 0.25 m^2 in cross section. Figure 18. below illustrates the system.

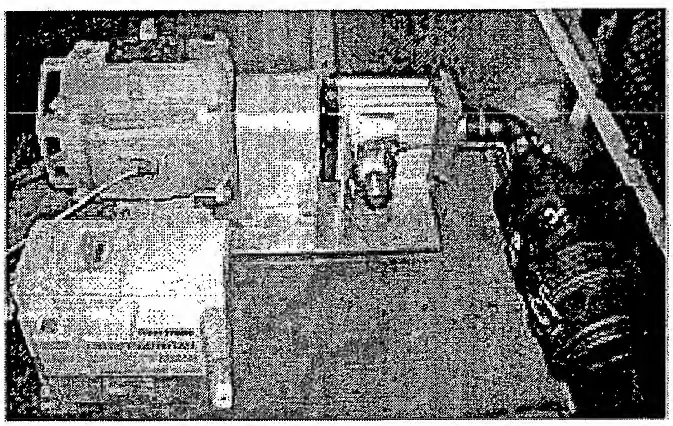

Figure 18. Air Delivery assembly

This assembly is large, and heavy for the application that it serves. This solution is one of the few products currently available that meet the design specifications.

Another aspect of the air supply fuel cell system that needs development is the inlet air temperature and humidity control. Currently, we are working with Porvair, a porous metal material supplier, to develop a device that regulates the temperature and humidity of inlet air stream to the fuel cell system. There is a considerable amount of energy (20 kW thermal) that needs to be added to the inlet air stream to achieve the desired characteristics (~ 70 deg C at 85 % RH). The challenge is that the heat and mass transfer must occur simultaneously. The current design, seen in figure 19, yields a device that is 0.3 m tall and 0.2 m in diameter with a weight of 10 kg.

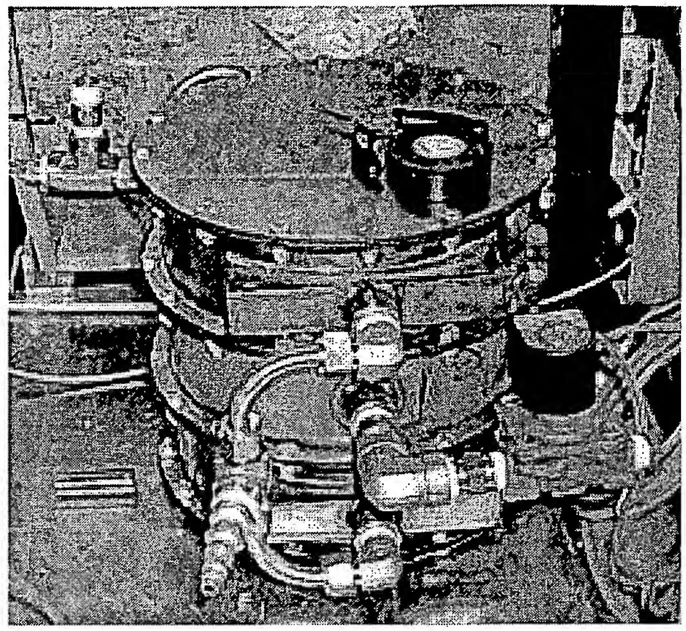

FIGURE 19. Air Humidification chamber

The current design has temperature and humidity control issues and the weight/size needs to be reduced.

CONCLUSION

A series hybrid PEM fuel cell sport utility vehicle has been modeled, designed, and built by the Hybrid Electric Vehicle Team of Virginia Tech for the FutureTruck Challenge. The ZE*burban* vehicle meets most of the goals and requirements for the competition. An efficient electric drivetrain combined with vehicle accessories, low rolling resistance tires, and properly sized battery and fuel cell subsystems results in combined city/highway fuel economy of 24 mpg (gasoline equivalent) or 1.4X the fuel economy of the stock vehicle. The ZE*burban* meets or exceeds the performance of the stock vehicle in most areas, including towing. Due to limitations of compressed gas hydrogen storage, the range of the vehicle is limited to 120 km (75 mi). The overall single speed gearing of the electric motors limits the top speed to 130 kph (80 mph). The consumer options and safety features have been maintained, including stock vehicle interior and exterior.

The lower greenhouse gas (GHG) emissions per unit energy of hydrogen fuel combined with lower energy consumption of the vehicle results in total GHG emissions of 135 gm/mile. This represents an 80% reduction in GHG emissions, exceeding the FutureTruck goal of 67% reduction. The ZE*burban* fuel cell vehicle is also locally zero emission with no evaporative emissions. A ground up redesign of this SUV could provide significant weight savings and allow packaging of fuel tanks to meet consumer requirements for range.

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